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Automated Loading and Unloading of CNC Vertical Milling Centers

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***Abstract*—The automation of loading and unloading operations for CNC vertical milling centers has become increasingly important due to rising production costs, labor shortages, and the pursuit of higher productivity and efficiency. This paper investigates the challenges associated with automating these processes, particularly focusing on optimizing workspace utilization, reducing auxiliary times, and improving overall workflow in CNC production environments. An overview of CNC technology development and its current capabilities is provided, highlighting the essential role of G-code programming and the transition from manual to computer-aided manufacturing. Key issues such as the high cost of programming for small batches, difficulty in recruiting skilled operators, and the economic factors influencing automation decisions are analyzed. The study emphasizes the critical importance of careful investment planning, including return on investment (ROI) considerations, productivity gains, and quality improvements. Practical guidelines for robot selection, end-effector design, and CNC-machine communication integration are proposed, along with a workflow model for automating part handling tasks. An experimental application on a VMC 1000L vertical milling center demonstrates the practical aspects and challenges of implementing an automated loading/unloading system, including necessary machine modifications like door automation. The paper concludes that although automation offers significant benefits, it is not universally applicable; a detailed feasibility study based on batch sizes, product complexity, and financial evaluation is crucial for success. Hybrid approaches combining manual and automated operations are suggested for flexible and cost-effective manufacturing strategies. The study highlights the growing role of intelligent automation as a response to market dynamics, labor trends, and technological advancements in the CNC manufacturing sector.**

***Keywords*— CNC machines, part loading, part unloading, robot integration**

I. Introduction

This paper suggests some considerations regarding CNC vertical milling centers and their loading and unloading operations in an automated manner.

CNC machines have gone through rapid development in the past 20-30 years from basic NC controls up to modern, 5-axis and more automated solutions. They are irreplaceable since most of the advanced parts are processed on such machines. On the market, there are 2.5D,

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3-axis, 3+2-axis and 5-axis machines. The difference between 3+2-axis and 5-axis is the simultaneous control of all axes on the 5-axis machine whereas the 3+2-axis only allows for indexing movements with the head that are not coordinated with the other axes.

A typical CNC machine has a steel table with slots for fixing parts, vices and other accessories, optionally a tool measuring system [1]. A rotary tool magazine with 16-30 tool slots is a nice automation solution. The CNC control varies from machine to machine with the most popular ones being Sinumerik 808D from Siemens, others are from the companies Fanuc, Heidenhain, Mazak, etc. The CNC system communicates with each CNC axis and sends commands to the drives, preferably via an Ethernet-based protocol.

CNC machines understand G-code, their native language. While there are some dialects of the language, generally all instructions are common with only minor differences. G-code could be typed manually. However, this is the old-fashioned way and nowadays CAM products are used. They obtain the part geometry from CAD models and the engineer has to define the corresponding operations (e.g. contour milling, pocket, profile) with their corresponding settings such as feed rate, spindle RPM, depth per pass, etc.). For each operation, the tool diameter and machining parameters must also be defined. Based on that, the CAM software product generates a file with G-code that could be transferred to the machine for direct processing. CAM products may be costly so the alternatives are manual typing and dialog-based programming, on the machine directly. The latter requires some experience but it is beneficial to invest in building these skills since this option most commonly is already provided with the machine delivery. Once the program is ready regardless of the way it is built, the machine needs a CNC operator who can start the cycle and observe the process for problems. There are no specific requirements for CNC operators as their sole job is to control the machine.

Universal machines on the other hand have no numerical control system. They require a machinist worker (which may also be referred to as an operator but it will not relate correctly to the CNC operators who tend to only observe while the machine is working). Some research papers indicate that in 2025 universal machines are not used or their use is limited. In fact, there is no place for comparison as there are certain operations that are much faster to process on universal machines rather than CNC machines. This is because a program is always necessary while with the universal machines one could directly start working. Despite the fact that no special skills are generally required for being a CNC operator, some companies struggle to find such workers and due to this shortage, they switch their focus on automation of loading, unloading processes as integration of automation solutions generally yields better productivity, quality and lower production costs.

The automation of loading and unloading is a process which makes use of robots (Cartesian, SCARA, six axis, delta) for the process of loading workpieces and unloading ready parts to/from the CNC machine.

II. Materials and Methods

A. Problem definition

The major issues with CNC machines are related to the costs of program preparation. In fact, for single parts or small batches it is not cost-effective due to the hour rate being paid to CNC programmers and/or CNC operators. In the general case, they are different people although in certain cases the role may be taken by a single person. In order to achieve efficiency, a certain machine has to produce parts as quickly as possible, to maintain high utilization throughout the workday, to be reliable and maintenance-free when there is work to be processed. If even one of these requirements fails, this immediately leads to production delays and triggers a chain of events failing other connected processes. Moreover, the loss of machine uptime directly affects overall shop productivity and customer satisfaction. Therefore, minimizing auxiliary times and optimizing setup operations are crucial for maintaining a competitive manufacturing process.

Table 1. Salaries of CNC programmers and operators by country

Country	***Average hour rate, EUR***	***Average hour rate, original currency***
Austria	18,67	same
Bulgaria	5	10,02 BGN
Czech Republic	7,98	199,65 CZK
Germany	19,41	same

The data in Table 1 shows the average hour rate that is paid in different countries for CNC programmers and operators [2]. As it could be noted from this example, sometimes two roles could be merged into a single job. The tendency is that more and more it becomes harder to produce by manual labor in Europe. This is especially true for Western Europe and still not so much in Eastern Europe. For this reason, automation is greatly involved in this area of the world and manual labor is only present with more technologically challenging processes which are hard to automate or it is not cost-effective.

The rise in costs is one of the general issues of production worldwide and solutions are constantly searched in the area of automation of the functions of CNC operators. It is unlikely that automation can fully replace CNC programmers, however it is not impossible with the recent development of AI tools. Perhaps it is powerful enough to do this by now but programs may need editing before running on the machine or costly failures may occur such as breaking of the spindle axis.

Automation and universality are normally mutually-exclusive terms. In other words, when a human CNC operator works, they could think and analyze and react in various situations. The automated system is programmed to perform a fixed number of operations, according to its algorithm (robot program, PLC program, etc.), in a fixed sequence. To achieve cost-effectiveness, medium to large batches (lots) are required. Automating the loading of a batch of only five consecutive parts is totally economically unjustified. Another motivation for installation of automatic loading/unloading solutions may be just for technological advancement of the company and not for financial reasons.

Perhaps a hybrid strategy may be employed - CNC operators may be available in the company, working at other positions, or at least on other machines. If a larger-series product (larger batch) is to be worked that could be handled by the automation system, then it may be loaded and unloaded automatically. However, if small batches of parts are present, it is better to work manually.

$$TC = MC + AT \quad (1)$$

TC – total cycle; MC – machine cycle; AT – auxiliary time, not overlapped

In (1) is shown the basic equation related to the calculation of the total cycle for one ready part. The machine cycle (MC) is normally not an object of optimizations, though sometimes this is also possible. The main focus goes on the auxiliary time that is not overlapped. In other words, it is production time that is spent while the CNC machine has stopped and there is no production process. AT consists of the sum of all activity durations such as door opening, part gripping/release, movement for loading/unloading, door closing. Regardless of the way these operations are handled, they are always not overlapped, they sum up and usually constitute a big portion of TC.

Business logic says that any investment should have a return on investment (ROI) period of about 2 years, on average. This is something like a rule of thumb that is considered. As a result, an estimation is to be made on the investment for consideration whether it would be effective.

$$I_{G_1} = (SC_0 - SC_a)QTY \quad (2)$$

I_{G1} – effect based on the difference in production costs; SC_0 – costs before the automation; SC_a – costs after the integration of the automation; QTY – year planned quantity.

$$I_G = I_{G_1} + I_{G_1}\left(\frac{K_1+K_2}{100}\right) \quad (3)$$

K_1 – rise of productivity; K_2 – decrease of failed products

$$A_M = \frac{K}{N} \quad (4)$$

A_M - Amortization; K –investment size; N – period of use of the equipment

$$n = \frac{K}{I_G+A_M} \quad (5)$$

n – period for return of investment

So equations (2), (3), (4), (5) are important in the decision-making process from economic point of view [3]. As already highlighted, ROI should be about 2 years. If we consider the influenced parameters, these are:

- costs after the integration of automation – it all depends on the level of automation and whether a human operator still has some role.
- yearly planned quantity – nowadays it is very rare that companies receive even frame purchase orders for a whole year ahead. The market is dynamic and not many producers could allow themselves to behave this way.
- Investment size – the amount of funds that the automated system costs. Perhaps a more cost-effective robot is better depending on its service life.

In the context of quality improvement, it may be considered that there will be significant values of coefficients K_1 and K_2 since it is expected that productivity will be increased. For K_2 it may not be so significant, however there may still be improvement. It is important to note that robots in comparison to humans are much better in repetitive tasks:

- no service breaks
- continuous operation without scheduled breaks (coffee and lunch breaks)
- efficiency $\geq$ 95% when programmed effectively
- high reliability when used according to the manufacturer’s recommendations

B. Possible solutions

Automation of loading and unloading is generally fulfilled with the help of robotic arms. Robots alone are insufficient unless combined with properly designed end effectors and suitable part magazines. The main parameters that have to be considered when integrating robots are:

- arm reach in relation to the CNC machine
- payload
- communications
- standard cycle time

Based on these, a suitable robot may be selected [4], [5]. Non-technical parameters include price, lead time and payment terms. Further technical considerations may include that the CNC machine must have capabilities for communication with external devices in order to exchange signals such as statuses, commands for start/stop/pause, etc. Luckily, most machines are robot integration ready due to the aforementioned economical factors.

A typical work cycle is shown in “Fig. 1”.

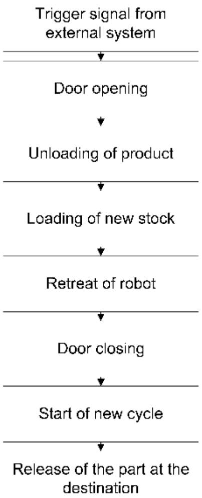

Fig. 1. Workflow related to CNC machine processing

The shown algorithm is limited to only the main stages. It could be definitely further developed to reflect some minor stages such as part fixing/release. It is considered that these processes are part of the loading/unloading processes. It is to be noted that the process of loading/unloading is identical regardless of the way it is carried out – by a human operator or by an automated system.

III. Results and Discussion

A. Experimental application

The decision making recommendations will be used for considerations on a VMC 1000L vertical milling center and it would be considered if it could be automated.

Fig. 2. CNC machine VMC 1000L

In "Fig. 2" is shown the general front view of the VMC 1000L machine. It features a Sinumerik 808D control from Siemens and all axes are based on servo drivers [6]. The machine features a 4th rotary axis that is inside the working area and a turret rotary magazine for tools. Furthermore, it has a chip removal conveyor [7],[8].

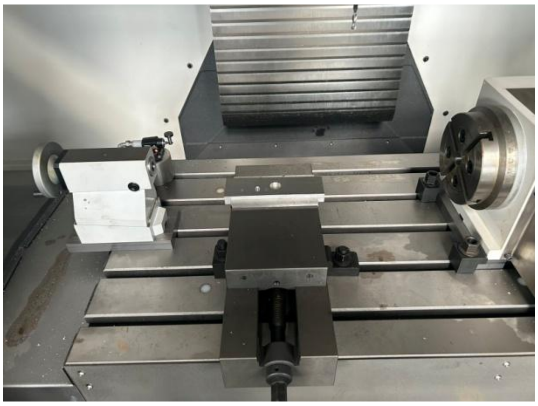

Fig. 3. Table, vise and 4th axis

In the current state parts are loaded manually in a vise ("Fig. 3") and the machine processes a hole on them. It is a simple operation that takes about 25 seconds. The auxiliary time would be much bigger.

One of the key issues related to the automation of this particular machine with a robot is that the door is not automatic and this requires the machine to be upgraded with actuators for opening and closing of the door. This should be done by means of electrical signals. The CNC controller is shown in "Fig. 4", it is a modern solution that is reliably established on the market. Many units are sold on a yearly basis. It is a high-quality industrial controller widely adopted in industrial practice, featuring many advanced features such as machine cycles, greatly reducing cycle times for repetitive operations. A few examples are – pocket milling, profile milling, drilling with cycles, etc. Many parameters could be customized and the CNC program takes only one row instead of multiple rows, based on simple G-code instructions.

Fig. 4. Control system

If the issue with the door is solved, the next step is to select a suitable robot. In order to have sufficient space for maintenance, it is advisable that the robot has an arm reach of at least 1200 mm which requires that a slightly bigger robot is integrated [9]. The example operation requires that the parts are stacked in a magazine next to the robot which involves hand labor [10]. This part is not prone to automatic feeding and orienting due to its dimensions and weight, regardless of the fact it is made from aluminum.

To provide an approximate quantitative assessment of the proposed automation concept, an engineering estimation of the cycle components was performed and presented in Table 2. The machine cycle remains unchanged at approximately 25 s, while the auxiliary time could potentially be reduced from approximately 20 s in manual operation to about 8 s under automated loading and unloading conditions. This results in an estimated reduction of total cycle time from 45 s to 33 s, corresponding to a productivity increase of approximately 36%. These values are indicative and depend on robot type, gripper design, communication delays, and part handling strategy.

TABLE 2. COMPARISON BETWEEN MANUAL AND ESTIMATED AUTOMATED OPERATION

Parameter	***Manual operation***	***Estimated automated operation***
Machine cycle, s	25	25
Auxiliary time, s	20	8
Total cycle time, s	45	33
Productivity increase, %	-	36.4%

IV. CONCLUSIONS

The automation of loading and unloading of CNC machines is still a highly relevant topic in 2026. However, not every task is worth automating and the feasibility greatly depends on various factors including economical ones. Sometimes one automation solution fails and the end result is negative (the process automation decreases productivity, quality and increases production costs). The decision making process should be carried out carefully and predictively, after evaluation of all aspects of the task [11]. Sometimes shop owners decide to automate not because of costs but due to the lack of personnel (in the scope of this paper that is CNC programmers and operators) and sometimes they do it due to the wish to have the latest technology in their facilities in order to present it in front of potential customers. The problem with personnel that has already emerged and there are multiple reasons behind it starting from school education and universities.

Miniature CNC machines are also very popular in jewelry processing and cost-effectiveness is more easily achieved in this sector of the industry due to the high-value products [12].

Precision and error handling are really important aspects of the process as feeding systems are demanding. Measures should be taken for repeatability and reliability in time using the methods presented in [13]–[15].

The physical parameters of machine parts affect the reliability of the developed feeding systems [16].

The provided methods and design suggestions in [17]–[18] are applicable to the development of automated robotic systems for loading and unloading operations in machining environments, where structural optimization and modular design play a key role in improving system efficiency and flexibility.

The hybrid stochastic–machine learning framework proposed in [19], although applied in a biomedical context, demonstrates a flexible data-driven approach that can be adapted for modeling, prediction, and optimization tasks in automated manufacturing systems.

The automation of CNC machines is a process that needs to go through the following steps:

- Evaluation of the economical effects and yearly quantity of parts.
- In case of positive results from the previous stage, a suitable robot has to be selected.
- A concept related to the automatic gripping and release of the workpiece on the machine table is to be considered.
- A robot with a sufficient arm reach has to be selected considering some extra reach.
- Analysis of the CNC machine and its features for automation – exchange of signals, reprogramming, etc.

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